JMEPEG (2009) 18:711–716
DOI: 10.1007/s11665-009-9383-0

1059-9495/$19.00

"One-Module"-Actuators Based on Partial Activation of Shape Memory Components

S. Langbein and E.G. Welp

(Submitted September 18, 2008; in revised form November 29, 2008)

An advantage of shape memory alloys (SMAs) is their potential to generate integrated actuator systems with a shape memory component. This can be accomplished for example by activating the thermal shape memory effect in selected regions of the SMA-component. We refer to this process as partial activation. The purpose of the present study is to find a way to create universal actuators with properties adjustable for various applications solely by partial activation. Thus, an object of investigation is the analysis of properties and capabilities of partial activation. Furthermore this study also implicates the survey of possibilities for partial power supply and electrical contacting. One possibility to use partial activation in integrated systems is given by the agonist-antagonist design. This type of design offers the advantage that a return spring or a mechanical brake for clamping the position without feeding electrical power is not necessary. On the other hand retention force is limited by the martensitic plateau and positioning accuracy by the elastic portion of mechanical stress. To solve these problems with constructive or control-oriented solutions is furthermore an aim of this study. Another approach is to use partial activation for influencing passive superelastic structures like hinges, dampers, or return elements by changing the austenitic plateau stress in integrated systems. To create a multifunctional integrated system, the NiTi-elements presented in this study offer various options since they apply partial activation both for thermal shape memory and for influencing super elasticity.

Keywords actuator, modular system, partial activation, shape memory alloys

1. Introduction

Integrated actuator systems begin to play a more and more important role. Above all in the field of microtechnology, conventional actuators will soon reach their limits and further miniaturizations are barely feasible so that new and particularly integrative solutions need to be developed (Ref 1). Especially in a critical environment like in fluids, in a vacuum or in clean rooms, systems are required that will not become affected by environmental conditions and vice versa which will have no impact on their environment, e.g., by polluting. Due to their considerable volume-specific work capacity, shape memory alloy (SMA) structures are particularly suitable for such kind of applications (Ref 2). In particular in microsystems technology and in micro assembly, there is a high demand for Smart Materials that can be produced in smallest dimensions and that are able to create considerable forces and large displacements. As for the applications, we can differentiate between tools or grippers for the manufacture and assembly of micro components and drives of micro systems. But also beyond microtechnology, the SMA prove of the potential to realize simple actuator systems based on integrated structures resulting in a reduced complexity and thus in a reduction of assembly costs and costs in general.

One ambition of this research project is to offer integrated actuators based on partial activation of shape memory components. While doing so, the complete system is not composed of several standardized components, as in a conventional sense, but a single, monolithic component is made available that can be divided into various, partial activatable regions. Such a SMA-component can be understood as an "one-module" or integrated modular system, with different local operating centers, which can be activated individually.

This article is an invited paper selected from presentations at Shape Memory and Superelastic Technologies 2008, held September 21-25, 2008, in Stresa, Italy, and has been expanded from the original presentation.

S. Langbein and **E.G. Welp**, Institute Product and Service Engineering, Ruhr-University Bochum, Bochum, Germany. Contact e-mails: langbein@lmk.rub.de and welp@lmk.rub.de.

2. Basis of Partial Activation

Compared to local configuration (Ref 3, 4) with partial activation the functional characteristics result only temporary by the heating of a particular part of the component zone. Therefore the phase change respectively the shape memory effect in operating condition is limited to this local area. A specific thermo-mechanical pre-treatment for the implementation of partial activation is not necessary. In this context general mechanisms used for thermal activation such as self-heating, thermal conduction, or thermal radiation are applicable as heating mechanisms. A valuation which sums up the activation processes is given in Table 1. With partial activation either the one-way effect or the two-way effect, or a

Table 1 Thermal methods of activation

Method of activation	Principle of operation	Advantages	Disadvantages
Heating by inherent resistance	The material is heated during current flow by its electrical inherent resistance	-Single partial activation possible -Heating is well controllable -Movement of the structure not interfered by activation principle -Quick response time	-Relatively high currents necessary -Contact for connection cable required
Heating by radiation	The material is heated by thermal radiation either by a radiation heater or a laser diode	-Contactless, no interference of movement	-High heat loss -Hardly controllable local heating -High complexity
Heating by heating elements	The material is heated by attached heating elements	-Single partial activation possible -Heating is well controllable	-Interference of movement by heating elements -Slower response time
Heating by induction	The material is heated by electromagnetic induction	-Contactless, no wiring effort regarding component -Quick response time	-High effort regarding constructive fitting of inductor coils -High currents necessary -Potential interference of movement by inductor coils

variation of the pseudo-elastic effect is implemented. The variation of the pseudo-elastic effect depends on the temperature sensitivity of the pseudo-elastic parameters, e.g., the pseudo-elastic plateau stress. A coexistence of both effects in one component as with local configuration is only possible, if the corresponding and dimensioned reset area is heated at first, to create superelastic characteristics. The warm-up period of the reset area only ends after a complete resetting of the structure. Depending on the structural design this process requires a local memory imprinting, as the reset area must be set under stress when the actuator area has reached its high-temperature form. The heating of pre-strained structure areas and the corresponding increase of its stiffness can also contribute to the improvement of the structural stability of such structures. As a result there are the following functional variants, which can be generated by partially activatable structures:

- actuator functions with the following characteristics:
  - standard design
  - agonist-antagonist design
  - step-actuator design
  - integrated return spring design
- pivotal functions with different stiffness
- spring functions with different stiffness
- damping functions with different damping characteristics.

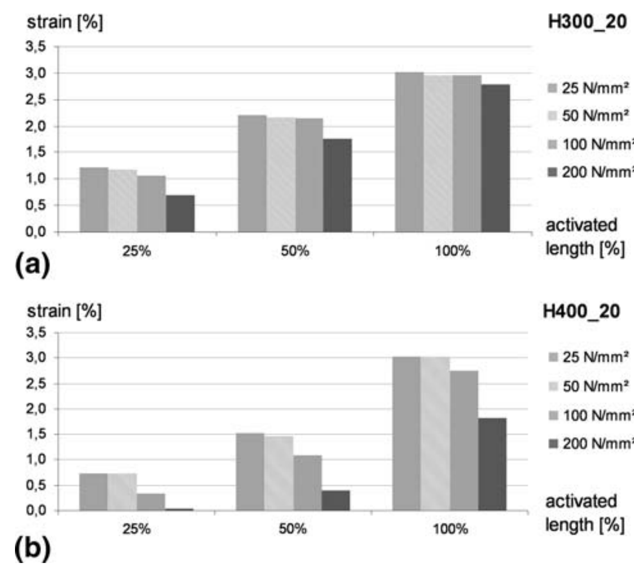


Fig. 1 Maximum strain of two wires with different thermo-mechanical pre-treatments

3. Experimental Pilot Surveys

The basic aim of the present study was to test the impact of partial activation on stress- and strain capability. Hereby the wire was activated in its full length, in half of its length and in one-fourth of its length. This activation was conducted with stresses of 25 N/mm^2, 50 N/mm^2, 100 N/mm^2, and 200 N/mm^2, to find out the exact impact of the stresses on the respective activation. A wire with the marking H (approx. 49.5 at.% Ni) with two different thermo-mechanical pre-treatments was used. The wire, cold shaped with 30%, was shaped by heat treatment once at 300 °C for 20 min and once at 400 °C for 20 min. After that the wires were electrically activated in a test rig by means of their inherent resistance. The contacting clamps were attached to the wires in distances of 25, 50, and 100%, relating to the clamped lengths of the wires. Hereby the displacement respectively the strain of the wire was measured. The results are presented in Fig. 1. In this context the maximum strain of the respective wires is related to the activated length occurring with different stresses.

The results show that the stress prevailing inside the wires can have a considerable impact on the strains of the partially activated wires. This results from the fact that with stresses above the martensitic plateau in combination with partial activation, the inactivated areas of the wire are expanded and that at the same time their strains seem to decline toward the periphery. The varying results of the two wires can be traced back to the fact that the 300-20 wire has a plateau stress of approx. 220 N/mm^2, while the 400-20 wire is at 100 N/mm^2. Therefore the strains of the 300-20 wire remain constant, while the 400-20 wire shows a significant strain loss at its periphery.

Another aspect that can be noticed while comparing both diagrams is that there are differences in strain value of the two wires, even at low stresses and strains. One can see that the 300-20 wire shows a strain of approx. 2%, e.g., at a stress of 25 N/mm^2 and an activated length of 50%, while the 400-20 wire on that condition only shows a strain of 1.5%. The reasons for this are the different A_S-temperatures of the two wires. With the 300-20 wire the temperature is 90 °C, with the 400-20 wire it is, however, 110 °C. This means that the existing thermal conduction within the wires and the low transformation temperature within the 300-20 wire cause a transformation of 50% of the wire's length respectively activate 50% of it. The basic experiments show that with the application of a partial activation in shape memory components, the load on the one hand and the transformation temperatures respectively the control accuracy on the other hand, has a considerable impact on the operating mode of these shape memory components. The outcomes of this are the following basic rules for the application of such components:

- The stress of the shape memory components must be clearly below the martensitic plateau stress,
- The heating of the areas which are to be activated should not exceed the transformation temperatures too much, to avoid a thermal conduction and with it an expansion of the areas which are to be activated,
- The reset force may not affect the activation cycle.

4. Experimental Surveys of Agonist-Antagonist Design

The problem of a variable reset force can be solved in an effective way by using the agonist-antagonist design. Another advantage of this construction design is that the intermediate positions can be kept continuously variable without the application of a mechanical construction. The positioning accuracy of this construction design, however, is a problem (Ref 5). Another problem is the regulation regarding the warm-up and cool-down periods. Figure 2 presents the different cool-down periods in a specified time frame. The heating-up period is always 3 sec.

One can observe that a steady-state equilibrium occurs between the two wires both at a cool-down period of 30, 10, and 5 sec. In addition to that, the force decreases to the same value in its currentless condition, whether the cool-down period is 30, 10, or 5 sec. This value is equivalent to the pre-stress of the wires due to assembly. The maximum value reaches a force of 14 N, which corresponds to about 200 N/mm^2. If the wires are warmed up immediately one after another without an adequate cooling phase, the force increases and with it the stress inside the wire increases considerably, too. The measured force will no longer be equivalent to the value of the pre-stress due to assembly. The forces between the wires rise up to 27 N which corresponds to a stress inside the wires of approx. 375 N/mm^2. Since the respective antagonist is not martensitic and for this reason not malleable, the agonist cannot develop its adjustment travel. The adjustment travel remains minimal with a value of only 1 mm. To achieve the same adjustment travel of about 5.5 mm, as in the 10 sec and 5 sec experiments, even without a cooling phase, one would need to extend the warm-up period of the agonist as well as the cool-down period of the antagonist. As the effectively sufficient conductor temperature increases due to the extended warm-up period, this would cause the warm-up period of the antagonist to be even longer. Furthermore the graph of the experiment significantly shows that there is a positioning deviation of approx. 1 mm—almost 20% of the adjustment travel—which occurs in every positioning step. The positioning deviation can be put down to the elastic portions of the martensitic deformation. In conclusion the experiments referring to the agonist-antagonist design show two things:

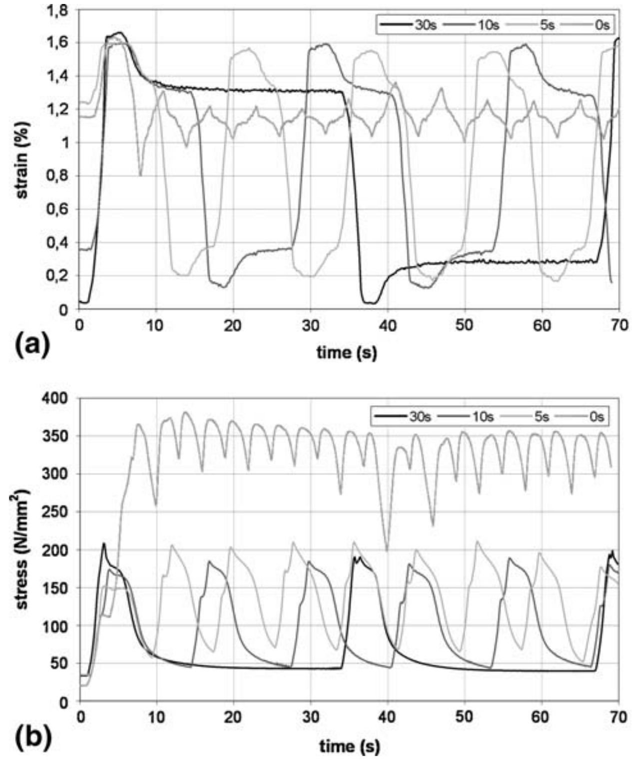


Fig. 2 Agonist-antagonist design wire actuator with different cool-down periods in a specified time frame

- There is a considerable positioning deviation, which can be reduced in technical applications by a positioning regulation.
- A precise regulation for the warm-up and cool-down periods needs to be made, so that the two wires do not work against each other while being in austenitic condition. This leads to high stress values inside the wire which can have a negative effect on the fatigue behavior.

The constructive solution of both regulating difficulties is a challenge for further research.

5. Development of Partial Activated Structures

5.1 Selection of Activation Method

There are various methods to activate the shape memory structures, which have been already mentioned in the previous paragraph. The presented activation methods are all in principle applicable for a partial activation of the structures. The advantages and disadvantages, given in Table 1, need to be considered to select the best possible operation and to meet the favoured requirements.

5.2 Selection of Connection Method

The easiest operation for partial activation is the heating by electrical inherent resistance. To employ this activation method, the connection between the actuators respectively the structures and the connection cable are necessary. There are different ways to establish this contact. First, there is the option to attach the connection cable to the shape memory structure by connection techniques such as substance-bonding, friction-locking, or form-locking. Second, there is the option to connect the structures via sliding contacts or similar. Within these two fields innumerable technical solutions exist already; one has to select the most adequate one. In general crimp or welded connections are suited for contact purposes.

5.3 Conceptual Design of Structures and Selection of Construction Design

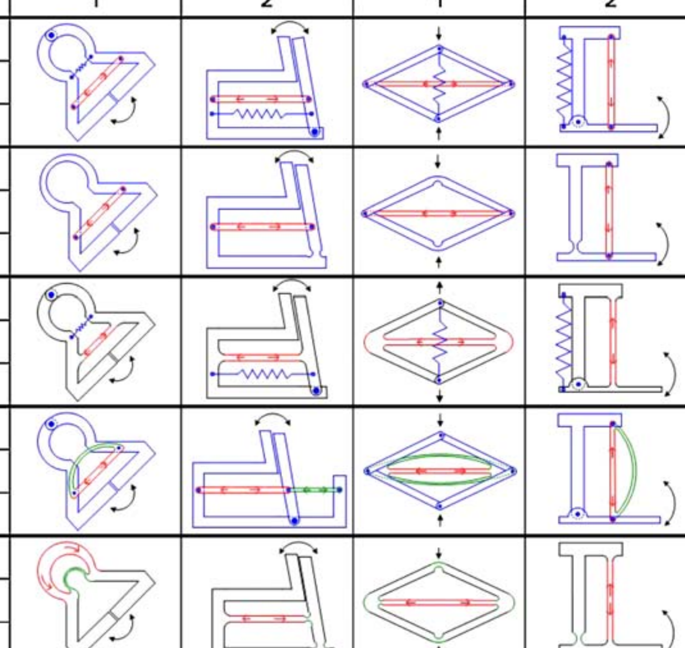
In general three types of construction designs can be distinguished, the differential construction design, the partial integral construction design, and the complete integral construction design. If one wants to implement the complete integral construction design and with it the "one-module"-module system, without using the agonist-antagonist construction design, it is an advantage to combine the partial activation with the local configuration as described in (Ref 3). Pseudo-elastic pivotal areas or when needed reset elements can only be integrated into the structure by local configuration. With pure local configurations a contact with the actuator area is not required because the entire component can be heated.

Tables 2 and 3 also show a systematic development of actuator structures, which are applicable for partial activation. Furthermore the conceptions take into consideration the combination with local configurations. For the development, selected basic structures were organized by suitable classification criteria and recorded in classification schemes. The presented structures are only an extract from an optionally expandable selection of solutions. Further solutions result from, e.g., a variation of the position of actuating elements and reset areas. Due to this variation other transmission ratios, adjustment forces, and travels can be implemented. An extension would also be achieved by connecting similar or separate structures or structure elements to complex or potential spatial structures.

The classification schemes which depict the structure synthesis are allied as follows: The structures are divided into return spring design (Table 2) and agonist-antagonist design (Table 3). Within the tables the structures are divided into gripper structures and movement structures. Two different basic structures are described each time. The rows are ordered, consecutively from top to bottom, and show the development of the integration potential. In row 1 the construction design is constructed completely differential, i.e., the carrier consists of steel or plastic, the resetting force is achieved by a steel spring or a second SMA-component. The shape memory effect only inherits the actuator functions. Such a construction design can only be found in SMA-based applications. Rows 2, 3, and 4 (rows 2 and 3 in Table 3) show partially integrated structures, in which the function integration develops via different parameters: In row 2 carrier and return spring are put together as one component (only by return spring design). Such an actuator is shown in (Ref 6). In row 3 (row 2 in Table 3) the carrier is manufactured from an SMA and connected with

Table 2 Systematic development of partially activatable actuator structures (return spring design)

partial activatable SMA-structures (return spring design)								
design	parts	material		integrated parts	gripper-structures		actuator-structures	
		SMA	no SMA		1	2	1	2
differential	carrier		X	-				
	return spring		X	-				
	SMA-component	X		-				
partial integrated	carrier		X	X				
	return spring		X	X				
	SMA-component	X		-				
	carrier	X		X				
	return spring		X	-				
	SMA-component	X		X				
	carrier		X	-				
	return spring	X		X				
	SMA-component	X		X				
integrated	carrier	X		X				
	return spring	X		X				
	SMA-component	X		X				



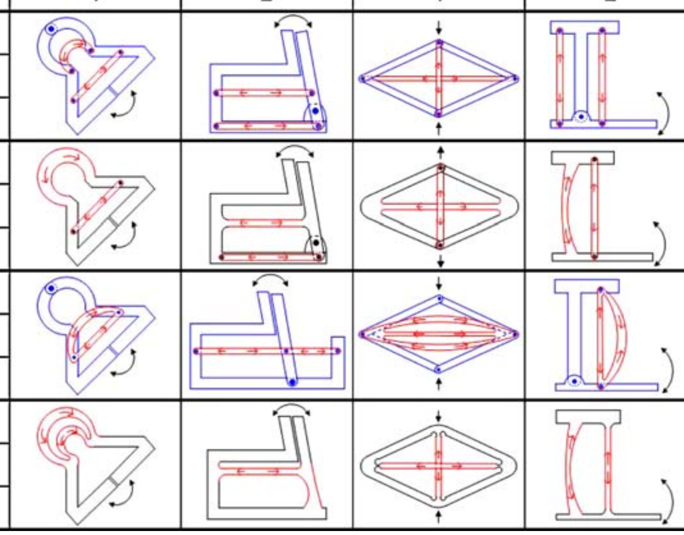
the shape memory actuator element to a single component. The return spring or the second SMA-component is separated. Row 4 (row 3 in Table 3) shows an assembly made of a carrier and a local set up of shape memory structure, which integrates actuating elements and reset elements. The solutions as given in row 5 (row 4 in Table 3) have a completely integrated, monolithic construction design and meet the criteria of a ''one-module''-module system. All functional and structural characteristics are combined in a single component. Thereby the solutions given in row 5 (Table 2) consist of an SMA with an in situ configuration of actuator areas and pseudo-elastic flexure hinges or of an SMA were the reset area is heated at first to perform structure deformation and resetting. The solution in row 6 has a similar assembly, differing only because here the reset element results from the agonist-antagonist principle.

5.4 Construction of a Demonstrator

Figure 3 shows the developed demonstrator. The system consists of four different components: bottom plate, bracket, lever arm, and the actuator wire. The actuator wire is conducted via a bore hole in the bottom plate to the corresponding bore hole in the lever arm. There the wire is fastened while the lever arm is in a horizontal position. Then the wire is connected via a required bore hole in the lever arm again. The bore hole depends on the required transmission ratio. The wire is fastened

Table 3 Systematic development of partially activatable actuator structures (agonist-antagonist design)

partial activatable SMA-structures (agonist-antagonist design)								
design	parts	material: SMA	material: no SMA	integrated parts	gripper-structures 1	gripper-structures 2	actuator-structures 1	actuator-structures 2
differential	carrier		X	-				
	SMA-component1	X		-				
	SMA-component2	X		-				
partial integrated	carrier	X		X				
	SMA-component1	X		X				
	SMA-component2	X		-				
	carrier		X	-				
	SMA-component1	X		X				
	SMA-component2	X		X				
integrated	carrier	X		X				
	SMA-component1	X		X				
	SMA-component2	X		X				



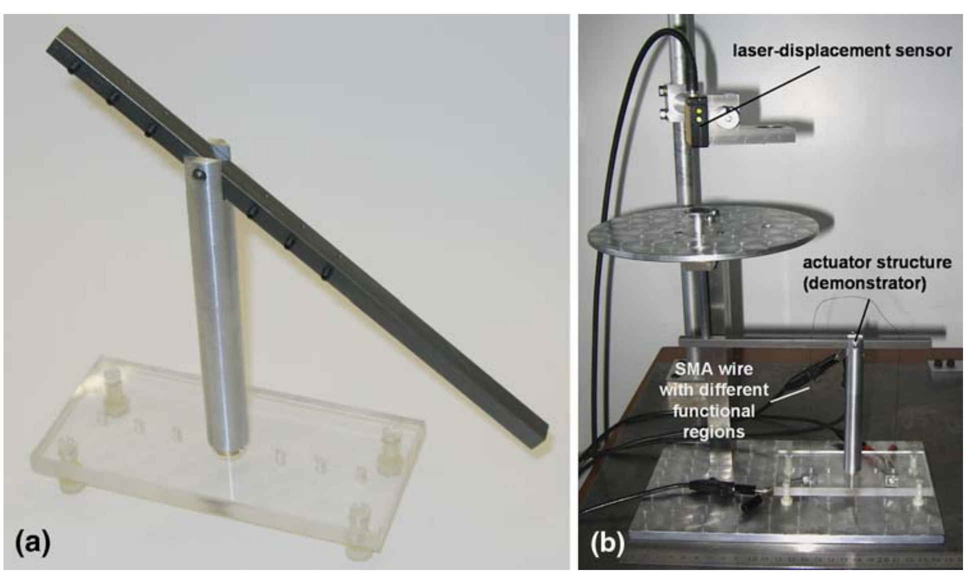


Fig. 3 Demonstrator and experimental setup

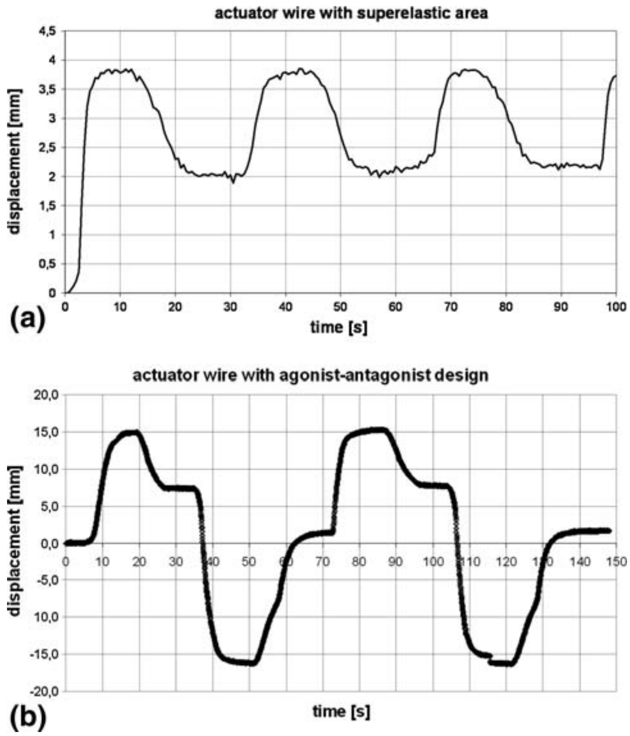


Fig. 4 Experimental results

for a second time and after that it is connected via the corresponding bore hole in the bottom plate again and it is clamped there. The actuator is now able to perform movements according to the agonist-antagonist principle.

The experimental results, generated by means of this demonstrator are presented in Fig. 4. On the one hand typical results of the agonist-antagonist design are displayed, but on the other hand Fig. 4 also shows results where the actuator wire was set up locally and therefore has superelastic characteristics on one side in order to initiate independent resetting.

6. Summary/Conclusions

The present research shows that it is feasible to generate "one-module"-modular system structures. These structures have the potential to increase standardization and the potential to reduce the number of components. Due to the manifold types of construction and movement these structures are particularly suitable to meet complex movement tasks. In micro technology as well, the idea of partial activation offers many possibilities. The problem of local heating and its associated contact could be solved by conductor paths integrated on the board, being built together with the actuator. For this reason partially controllable actuator arrays could be generated in a simple way. Furthermore the basic experiments have identified, the problems occurring with the application of partial activation and the agonist-antagonist design and how these problems can be solved in technical systems.

References

1. H. Janocha, *Adaptronics and Smart Structures-Basics, Materials, Design and Applications*, Springer-Verlag, Berlin, Heidelberg, New York, 1999
2. Å. Burman, E. Møster, and P. Abrahamsson, *On the Influence of Functional Materials on Engineering Design, Research in Engineering Design*, Springer-Verlag, London, 2000
3. S. Langbein and E.G. Welp, *Generation of Smart Structures on the Basis of In Situ Configuration of Shape Memory Alloys, Advances in Science and Technology*, Vol 59, Trans Tech Publications, Switzerland, 2008, p 184–189
4. Y. Bellouard, T. Lehnert, J.-E. Bidaux, T. Sidler, R. Cavel, and R. Gotthardt, Local Annealing of Complex Mechanical Devices: A New Approach for Developing Mono-Lithic Micro-Devices, *Mater. Sci. Eng.*, **A273–275**, p 795–798, Elsevier Science, 1999
5. M. Kohl, *Entwicklung von Mikroaktoren aus Formgedächtnislegierungen*, Dissertation, Forschungszentrum Karlsruhe, 2002
6. S. Langbein, E.G. Welp, and J. Sohn, Development of a Variable and Integratively Structured SMA-Actuator for Multifunctional Application, *Proceedings of the 11th International Conference on New Actuators*, Bremen, 2008